

## CHAPTER 142

### WAVE FORCES ON VERTICAL PILES CAUSED BY 2- AND 3-DIMENSIONAL BREAKING WAVES

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#### ABSTRACT

The present study deals with analysis of results from a new experiment in which local wave forces on a vertical pile penetrating the free surface were measured, both in transient breaking waves and in 2- and 3-dimensional irregular seas, regular waves, and waves and uniform currents superposed. The performance of the entire experimental programme showed that extreme wave load intensities are associated with transient 2- or 3-dimensional breaking waves, of relatively short wave periods, and not with the highest waves in the simulated sea states. The total integrated in-line force and the total overturning moment caused by breaking waves exceeded the values measured in monochromatic regular waves by a factor of 3. Inception of wave breaking was caused by phase superposition, and occurred also for very low values of wave steepness  $s = 0.05$ .

#### 1 INTRODUCTION

The study of breaking waves in deep waters was initiated in Norway after a quite large number of capsizings of cargo vessels and fishing trawlers, which had occurred over a few years. Kjeldsen & Myrhaug (1980) analysed field data from 22 gales, and found encounter probabilities for high and steep waves occurring in deep water conditions based on multivariable probability density functions. After this Kjeldsen (1982) developed a non-linear wave generation technique, based on sweep frequency modulation with the ability to produce breaking freak waves with a control of breaker type (spilling, bore, plunging) within a hydrodynamic laboratory. Application of such a technique produces violent plunging breakers at a specified position and time in a wave basin. The plunging breakers occur in deep water and repeat with great accuracy. Further the position of the plunging jet can be shifted horizontally according to rules for non-linear dispersion of transient wave trains. In addition the particle velocities within the crests of these transient plunging breakers in deep waters were measured. This was achieved with a newly developed wave-follower-system, consisting of a carriage with a high-speed cine camera and a current meter that followed one particular wave crest

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until it finally became unstable and developed into a plunging jet, see Kjeldsen (1984a). The very large particle velocities measured in the upper part of the crests suggest that local wave forces in breaking waves close to the free surface should be much higher than predictions of wave forces obtained from application of Stokes' higher order wave theories. Wave forces measured on piles in the Mexican Gulf during Hurricane Carla, were analysed by Dean, Dalrymple and Hudspeth (1981), who found quite a reduction in measured wave forces close to the free surface in the crests of the waves. It was then found that theoretical predictions of wave force, based on higher order Stokes' theories, in general overestimate the local wave force in a local area close to the free surface. Therefore, in order to investigate the intensity of local wave forces very close to the free surface in breaking and non-breaking wave crests, an extensive experimental programme was performed in the large new Ocean Simulating Basin at MARINTEK, Trondheim, Norway. The problem we consider is the following: a vertical pile encounters wave crests, which can be 3-dimensional as Fig. 1 shows, or 2-dimensional swell. The wave crests considered here can be either breaking or non-breaking.

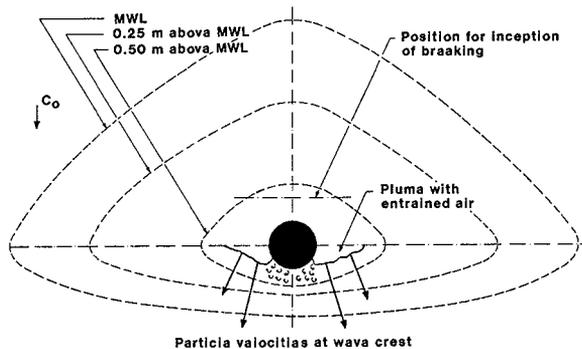


Fig. 1 Definition of problem. Contour lines of a 3-dimensional wave crest near the pile are shown. The wave crest has a very steep front and a less steep rear side. The position for inception of breaking can be controlled. The horizontal particle velocity vectors at the free surface of the upper part of the crest are shown. The ratio between the magnitudes of these vectors and linear phase velocity (shown in upper left corner) is nearly 3.

We focus on force measurements in the upper part of a breaking wave crest. Here the flow is not oscillatory, but it is an accelerating and decelerating flow where the horizontal particle velocity component maintains mainly the same direction. Therefore eddies released behind the pile will not be swept backwards and return in the following wave, as the case is in the fully submerged part of the pile.

Thus the separation points in this upper part of the wave crest will be shifted. In addition air entrainment takes place when the waves break. Thus Morison's equation is probably not the best force model to describe such a complicated situation. Emphasis should be given to the 3-dimensional character of the problem. Lift force components of considerable magnitude was found to occur. In the present study in-line forces are defined as force components acting in the main wind direction, which also is assumed to be the main direction for wave propagation in a simulated 3-dimensional sea. These are considered to be mainly drag forces. Lift forces or transverse forces are defined as force components acting perpendicular to the main wave direction.

## 2 EXPERIMENTAL PROGRAMME

In order to investigate the intensity of local wave forces very close to the free surface in wave crests, an extensive experimental programme was performed in the new Ocean Simulating Basin at MARINTEK, Trondheim, Norway. This basin has the following main dimensions: length - 80 m, width - 50 m. It is equipped with an adjustable bottom that permits water depths in the range 0.1 - 10.0 metres.

Experiments can be carried out with maximum wave heights close to 1.0 m and wave periods in the range 0.5 - 3.6 seconds. It is also possible to superpose waves upon uniform currents with logarithmic profiles. The present experiments were performed with a water depth of 3 metres, corresponding to deep water conditions.

A vertical pile with a diameter of 60 mm (a leg of a steel jacket platform in scale 1 : 25) was installed with 26 shear force transducers mainly located in the zone between the highest wave crest and the lowest wave trough. Each shear force transducer consisted of a 15 mm wide horizontal ring. Force measurements on each ring were obtained by strain gauges. In addition to local measurements of in-line and transverse forces on the pile, sea surface elevations, uniform currents and directional wave spectra were measured. An experimental programme was then performed containing the following test conditions:

| SEA SIMULATION  | Hydraulic<br>Double Flap<br>Wave Generator | Hydraulic<br>Double Flap<br>Wave Generator<br>with Steady<br>Uniform Current<br>Superposed | Electric<br>Multi Flap<br>Wave Generator<br>with<br>144 Elements |
|---|--|--|--|
| REGULAR 2-DIMENSIONAL WAVES   | 20   | -  | -  |
| 2-DIMENSIONAL IRREGULAR SEA<br>WITH PIERSON-MOSKOWITZ SPECTRA                     | 15   | -  | -  |
| 2-DIMENSIONAL TRANSIENT FREAK<br>WAVES, PLUNGING BREAKERS                         | 20   | -  | -  |
| A UNIFORM CURRENT WITH<br>2-DIMENSIONAL IRREGULAR SEAS<br>SUPERPOSED (PM-SPECTRA) | -  | 12   | -  |
| 3-DIMENSIONAL IRREGULAR SEAS<br>WITH PIERSON-MOSKOWITZ AND<br>JONSWAP SPECTRA     | -  | -  | 10   |
| 3-DIMENSIONAL SHORT CRESTED<br>BREAKING FREAK WAVES, SPILLING<br>BREAKERS         |  |  | 10   |

Total : 87

Fig. 2 shows a vertical section of the pile with the distribution of shear force transducers. The right hand side of this figure shows flow patterns at various horizontal planes behind the pile as functions of Reynolds and Keulegan-Carpenter numbers. In the present investigation Reynolds numbers in a range of 0 -  $2.9 \cdot 10^5$  and Keulegan-Carpenter number in a range of 0 - 135 were achieved. Data acquisition took place on 63 channels simultaneously with a sampling frequency of 20 Hz. Data acquisition in the Ocean Basin took place for 5 minutes in each experiment, and for some experiments with irregular seas, data acquisition was extended to 20 minutes.

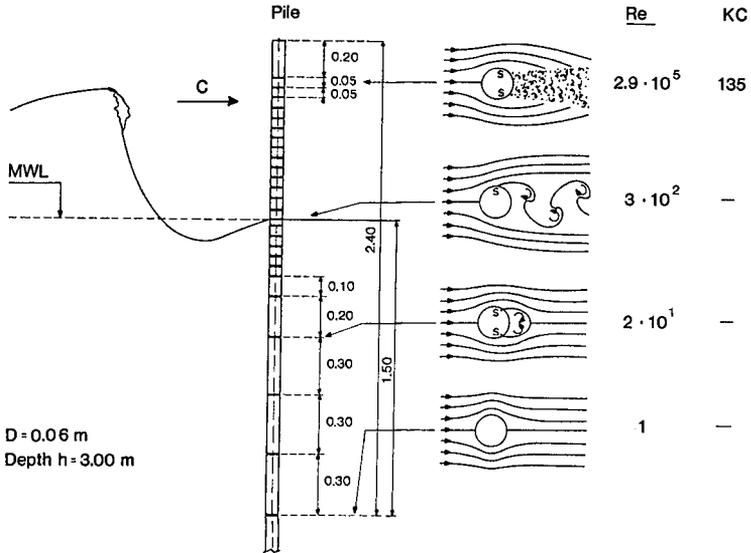


Fig. 2 Left: Experimental arrangement. Right: Flow patterns and eddy development in horizontal planes behind the pile at various elevations, shown as functions of Reynolds and Keulegan-Carpenter numbers.

### 3 RESULTS

The main result from the entire programme was that the 2-dimensional breaking waves occurring in deep waters as plunging breakers gave far the largest wave forces. These particular waves were generated as a superposition of 43 frequencies contained in a wave group. By means of a non-linear amplitude-dependent sweep frequency modulation, the breaking waves were obtained right on the structure. Fig. 3 shows an example of the measured surface elevation of such a wave. The wave shown in this particular example had a zero-downcross wave height  $H_{zd} = 0.504$  m, a zero-downcross wave period  $T_{zd} = 1.385$  sec, a horizontal asymmetry factor  $\mu = 0.879$  and a crest front steepness  $\epsilon = 0.539$ . (For definition of  $\mu$  and  $\epsilon$ , see Kjeldsen & Myrhaug (1980).)

Fig. 3 also shows the measured in-line and transverse force components in this kind of wave. The lift force component is close to 20 % of the measured drag component and should be taken into consideration in design. The particular shape of the lift force component shown in Fig. 3, indicates that eddy shedding takes place.

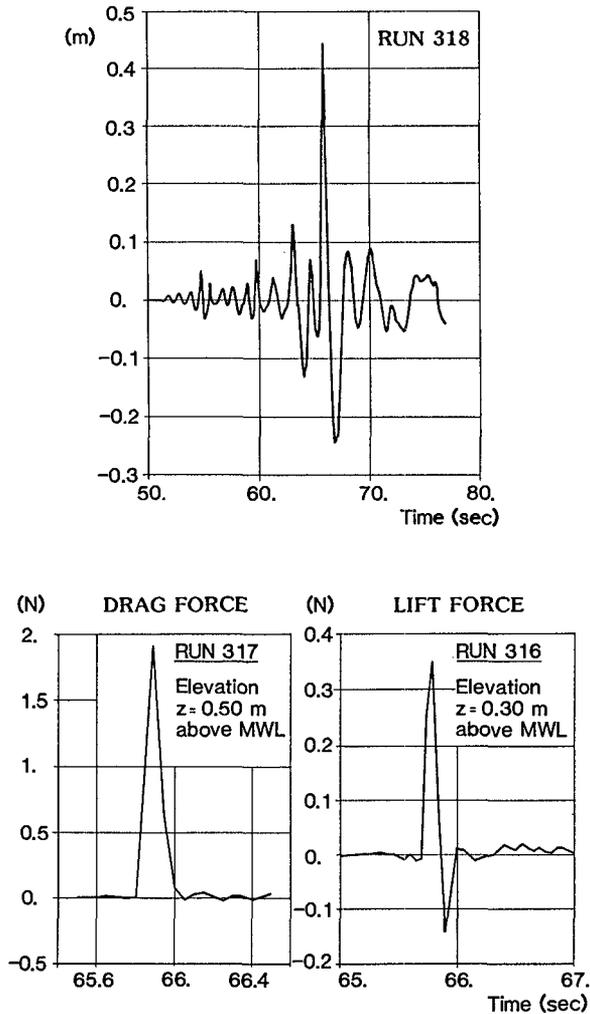


Fig. 3 Above: Surface elevation of a 2-dimensional transient freak wave breaking as a plunging breaker. Below: Drag- and lift force components measured in such waves above mean water level (MWL).

Fig. 4 shows a remarkable result. In this particular example a wave group consisting of 3 waves were obtained at the pile. The upper left corner in Fig. 4 shows the surface elevation of these waves. The first wave is small and unimportant. The second wave A is breaking violently as a plunging breaker. The third wave B is a regular wave very similar in shape to predictions made by Stokes 2-order wave theory. Wave B has a much longer wave period than wave A and we should thus expect that the associated wave kinematics and also the resulting drag force component are higher in wave B than in wave A. However, the measured drag force components shown in Fig. 4 clearly demonstrate that the transient wave A, breaking as a plunging breaker gives rise to much higher drag forces at all levels. This can be explained by the fact that the breaking wave is generated as a phase superposition of many individual waves, and thus contains much more wave energy in the crest, than the higher wave B. This is the case even when wave B has a longer zero-downcross wave period.

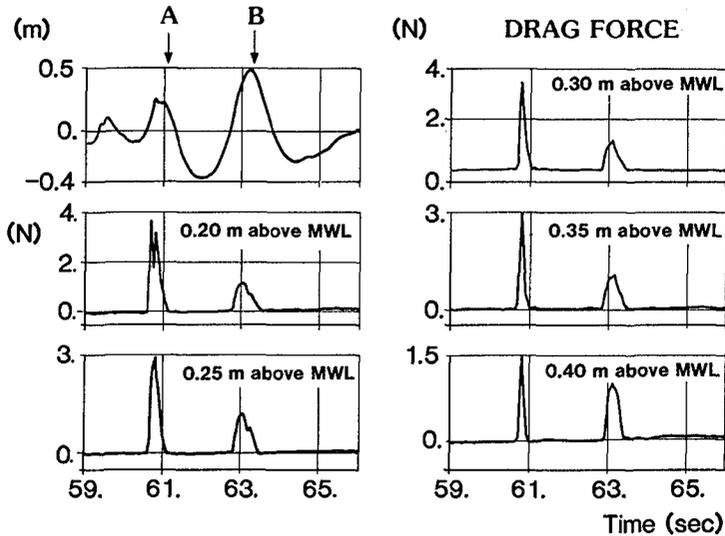


Fig. 4 Upper left: Surface elevation of wave group. Wave A is a plunging breaker. Wave B is a higher more regular wave with a longer wave period. Below and right: Drag force components measured for wave A and wave B above MWL.

Fig. 5 shows a comparison of the vertical profiles of maximum local instantaneous drag forces obtained in a plunging breaker and obtained in a test series with regular monochromatic waves which turned out to have profiles very close to those predicted by Stokes 2. order wave theory. We see in Fig. 5 that the plunging breaker has a maximum local wave force that is close to 5 times larger than the maximum local force obtained in the monochromatic wave.

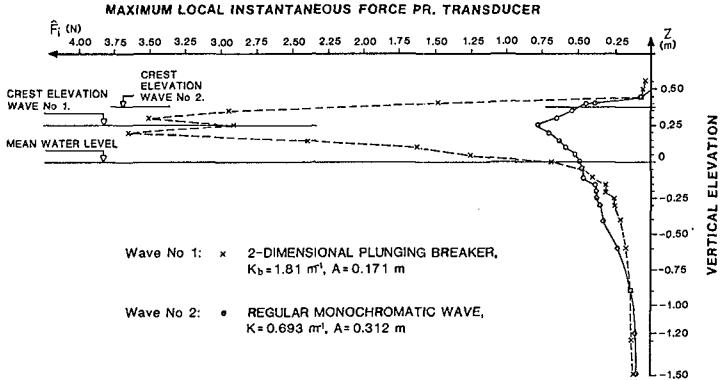


Fig. 5 Comparison between vertical profiles of maximum drag force obtained in plunging breaker and obtained in test series with regular monochromatic waves. (K is the wave number, and A is the wave amplitude H/2.)

Not only the local wave force, but also the total integrated drag force was much higher in the breaking wave than the corresponding drag force in the monochromatic wave. A factor of nearly 3 was found. Fig. 6 shows integrated in-line forces for breaking waves and results for monochromatic waves plotted as a function of wave steepness. Also the envelope for the tests with breaking waves is indicated. It is remarkable that plunging breaking waves were found to occur with steepnesses as low as 0.05. Other breaking wave transients occurred with steepnesses as high as 0.191. Thus it is obvious that the theoretical limiting steepness for monochromatic waves  $s \approx 0.141$  can not be used to predict inception of breaking in transient or random waves. (See also Kjeldsen (1984b) and DoId and Peregrine (1986).)

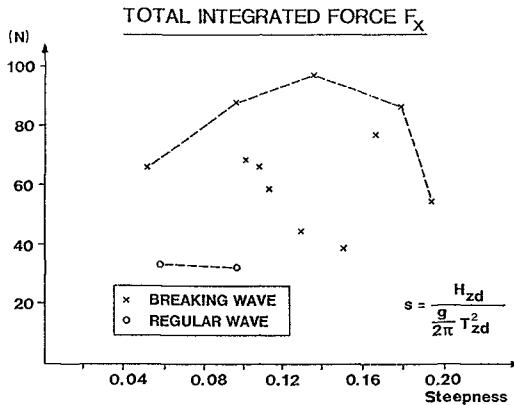


Fig. 6 Total integrated force in breaking waves compared with the total integrated force in regular waves with comparable steepnesses.

Also the total overturning moment was much higher for the breaking waves than for the monochromatic waves. Also here a factor of nearly 3 was found. The contributions from the drag force components near the free surface to the total overturning moment  $M_y$  at the seabed become more and more important when structures are developed for deeper waters, see Fig. 7. Results can also be presented in 3-dimensional plots as functions of wave height  $H_{zd}$  and wave period  $T_{zd}$ .

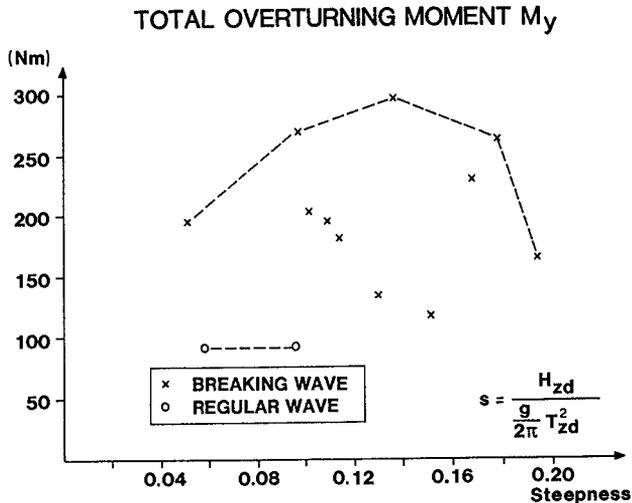


Fig. 7 Total overturning moment in breaking waves compared to total overturning moment in regular waves with comparable steepness.

We now proceed to 3-dimensional short-crested breaking waves occurring in deep water. These waves were focussed over a sector angle nearly 98 degrees. We attempted to model a situation with crossing wave orthogonals in deep water, such as can occur leeward of islands and reefs due to topographic refraction. The short-crested breaking waves were obtained using one frequency and waves approaching from 144 directions towards a focussing point with crossing orthogonals. They were generated with the 144 electrically driven flaps for 3-dimensional sea generation. Fig. 8 shows an example of such a short-crested 3-dimensional breaking wave. (See also Kjeldsen & Åkre (1985).)



Fig. 8 Short-crested 3-dimensional breaking wave with zero-downcross wave height  $H_{zd} = 0.692$  m and zero-downcross wave period  $T_{zd} = 1.69$  sec. The steepness  $s_{zd}$  based on these parameters is  $2\pi H_{zd}/g \cdot T_{zd}^2 = 0.155$ .

Fig. 9 shows an overall non-dimensional comparison of obtained results. Dimensionless local mean pressure  $\Omega$  is plotted against dimensionless vertical elevation. The mean pressure  $\bar{p}_i$  is defined as  $\hat{F}_i/D \cdot t'$ , where  $\hat{F}_i$  is the maximum instantaneous wave force measured in the wave dispersion direction,  $D$  is the diameter of the pile, and  $t'$  is the width of the shear force transducer.

The wave number  $K_b$  at the position where inception of breaking takes place is defined as  $K_b = 4\pi^2/g \cdot T_{zd}^2$  where  $T_{zd}$  is measured at the position where the wave profile becomes vertical.

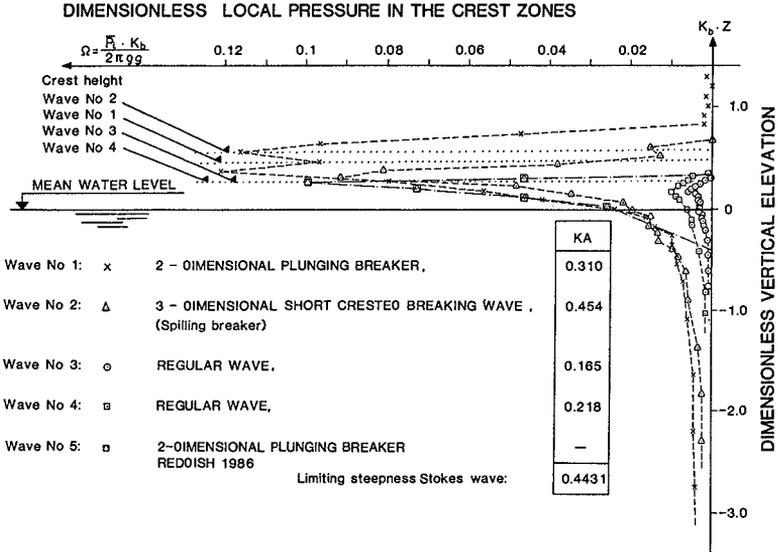


Fig. 9 Comparison between dimensionless local mean pressure in the crest zones measured in 2-dimensional plunging breaker waves, 3-dimensional short crested breaking waves, and 2-dimensional monochromatic waves. (K is wave number, A is wave amplitude H/2.)

The 2-dimensional plunging breakers gave the highest local forces, the highest integrated forces and the highest overturning moments in the entire test programme. The 3-dimensional short-crested breaking waves gave high but somewhat less forces, due to the angular spreading of crest particle velocities. Shown here are also results for a shallow water breaking wave measured by Reddish (1986). Reddish found local wave forces at the same level as the present investigation. However, numerical simulations of kinematics in deep and shallow water waves made by Vinje & Brevig (1981) show that kinematic vectors in breaking wave crests attain larger values in shallow waters than in deep waters. We should therefore expect that also wave forces associated with shallow water breaking waves are higher than the forces associated with deep water breaking waves which are reported here. Tørum (1985) performed an in-depth analysis of measured in-line wave forces associated with regular monochromatic waves. (See also Dean, Tørum, Kjeldsen (1985).)

It is important to be aware of the fact that wave impact or wave slamming is not incorporated in the present investigation. Data was sampled with a frequency 20 Hz. Wave impact forces have durations of the order  $1 \cdot 10^{-3}$  sec and that demands much higher sampling frequencies. If wave impact forces occur these forces must be added to the viscous wave forces reported here. A separate investigation of a vertical and tilted plate exposed to impacts from crests of deep water breaking waves was performed by Kjeldsen (1981).

#### 4 WAVE KINEMATICS

The present study is extended to include wave kinematics. Melville (1983) has shown that the Hilbert transform can be used to measure the amplitude, frequency, wave number and phase velocity as continuous variables even in a strongly non-linear unsteady wave train. In the present study application of the Hilbert transform is extended to include a continuous calculation of the horizontal and vertical particle velocities at the free surface based on measurements of free surface elevation. Fig. 10 presents results of such a calculation. It was found to predict wave kinematics at the free surface, even in very non-linear waves close to inception of breaking. For further details, see Kjeldsen (1986).

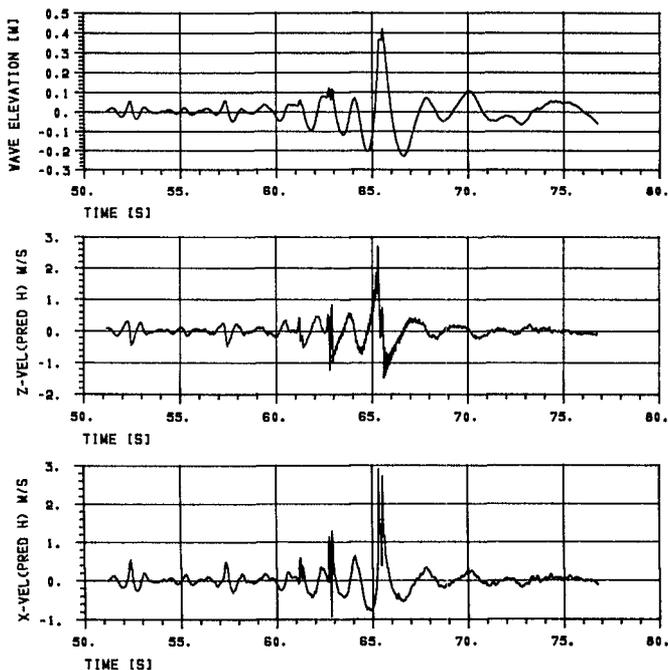


Fig. 10 Surface elevation and predicted horizontal and vertical particle velocities.

## 5 INSTABILITY OF 3-DIMENSIONAL WAVES

Su, Bergin, Marler and Myrick (1982) found that 3-dimensional subharmonic bifurcation of 2-dimensional wave trains can occur when the wave steepness exceeds  $ak \geq 0.25$ . As a result 3-dimensional spilling breakers are generated with large crest front steepnesses. During this process, two series of oblique wave groups are formed and radiate symmetrically away from the primary wave direction at a constant angle of about 30 degrees. These spilling breakers are thus examples of a source of directional spreading of wave energy. Such a mechanism can also explain the presence of breaking waves in deep waters. This phenomenon has also been observed in the Ocean Basin.

## 6 CONCLUSIONS

- 1) The performance of the entire experimental programme showed that extreme wave load intensities are associated with transient 2- or 3-dimensional breaking waves, of relatively short wave periods, and not with the highest waves in the simulated sea states.
- 2) Local wave pressures measured close to the free surface in the crests of transient 2-dimensional plunging breakers exceeded local wave pressures in monochromatic regular waves by a factor of 5. The regular waves had surface elevations very close to predictions made from Stokes' second-order wave theory.
- 3) The total integrated forces and the total overturning moments in breaking waves exceeded those measured in regular monochromatic waves by a factor of 3.
- 4) Local wave forces measured in 3-dimensional short-crested breaking waves were lower than local wave forces measured in 2-dimensional plunging breakers. This result can be explained by the fact that horizontal crest particle velocities in general are lower in 3-dimensional waves than corresponding horizontal crest particle velocities in 2-dimensional waves.
- 5) Inception of wave breaking was caused by phase superposition, and occurred also for very low values of wave steepness  $s = 0.05$ .
- 6) Our final recommendation is therefore that much more attention should be given to breaking waves, and that experiments of the kind reported here be extended in the future to include breaking waves also in shallow water and breaking waves occurring on beaches.

## 7 ACKNOWLEDGEMENTS

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## APPENDIX

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